Global fit on the solar (and other) neutrino results

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General three-neutrino framework

- Equation of motion: **6 parameters** (including Dirac and neglecting Majorana phases):

$$i\frac{d\vec{\nu}}{dt} = H\,\vec{\nu}; \qquad H = U_{\text{vac}} \cdot D_{\text{vac}} \cdot U_{\text{vac}}^{\dagger} \pm V_{\text{mat}};$$

$$U_{\text{vac}} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}\,e^{-i\delta_{\text{CP}}} \\ 0 & 1 & 0 \\ -s_{13}\,e^{i\delta_{\text{CP}}} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \cancel{\begin{pmatrix} e^{i\eta_1} & 0 & 0 \\ 0 & e^{i\eta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}}, \qquad \vec{\nu} = \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix};$$

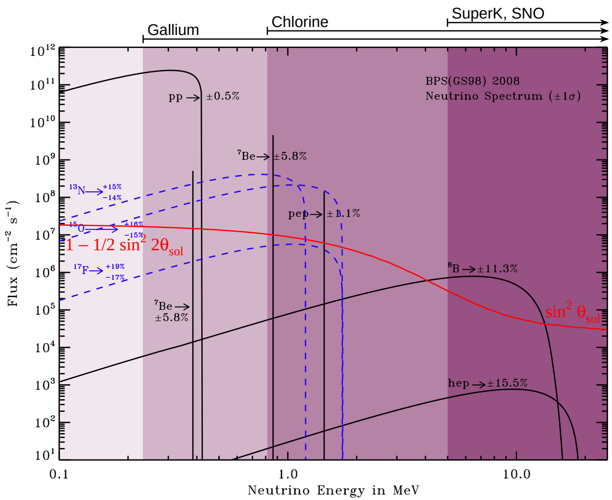
$$D_{\text{vac}} = \frac{1}{2E_\nu}\Big[\text{diag}\,(0,\, \Delta m^2_{21},\, \Delta m^2_{31}) + \cancel{m_1^2 I}\Big]; \qquad V_{\text{mat}} = \sqrt{2} G_F N_e\, \text{diag}\,(1,\, 0,\, 0)\,.$$

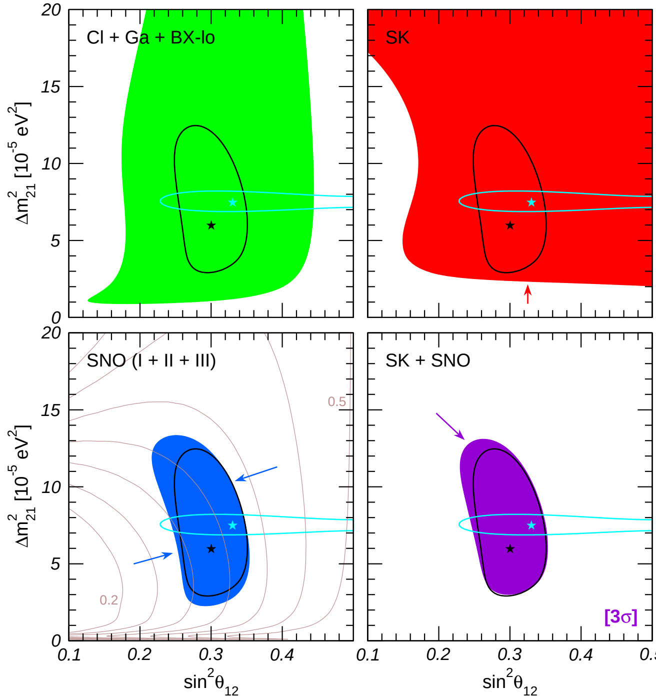
6 parameters $\Longleftrightarrow$ 6 types of experiments

- **SOLAR** sector:
  - – solar experiments (mainly SNO) $\longrightarrow \theta_{12}$
  - – rector VLBL (KamLAND) $\longrightarrow \Delta m^2_{21}$
- **REACT** sector:
  - – rector LBL (Double-Chooz, Daya-Bay, Reno) $\longrightarrow \theta_{13}$
- **ATMOS** sector:
  - – atmospheric experiments (SK) $\longrightarrow \theta_{23}$
  - – accelerator LBL-DIS (Minos $\nu_\mu \to \nu_\mu$) $\longrightarrow \Delta m^2_{31}$
  - – accelerator LBL-APP (Minos $\nu_\mu \to \nu_e$, T2K) $\longrightarrow \delta_{\text{CP}}$

Solar sector: anatomy of the oscillation solution

- $\theta_{13} = 0 \;\Rightarrow\; i\dfrac{d\vec{\nu}}{dt} = \left[\dfrac{\Delta m^2_{21}}{4E_\nu}\begin{pmatrix} -\cos 2\theta_{12} & \sin 2\theta_{12} \\ \sin 2\theta_{12} & \cos 2\theta_{12}\end{pmatrix} \pm \sqrt{2}\,G_F \begin{pmatrix} N_e & 0 \\ 0 & 0 \end{pmatrix}\right]\vec{\nu}$, with $\vec{\nu} = \begin{pmatrix}\nu_e \\ \nu_a\end{pmatrix}$;
- Data: $\begin{cases} \text{low-E (Cl, Ga): } P_{ee} \approx 1 - \frac{1}{2}\sin^2 2\theta_{12}, \\ \text{high-E (SK, SNO): } P_{ee} \approx \sin^2\theta_{12}; \end{cases}$
- tension between solar and Kam best-fits.



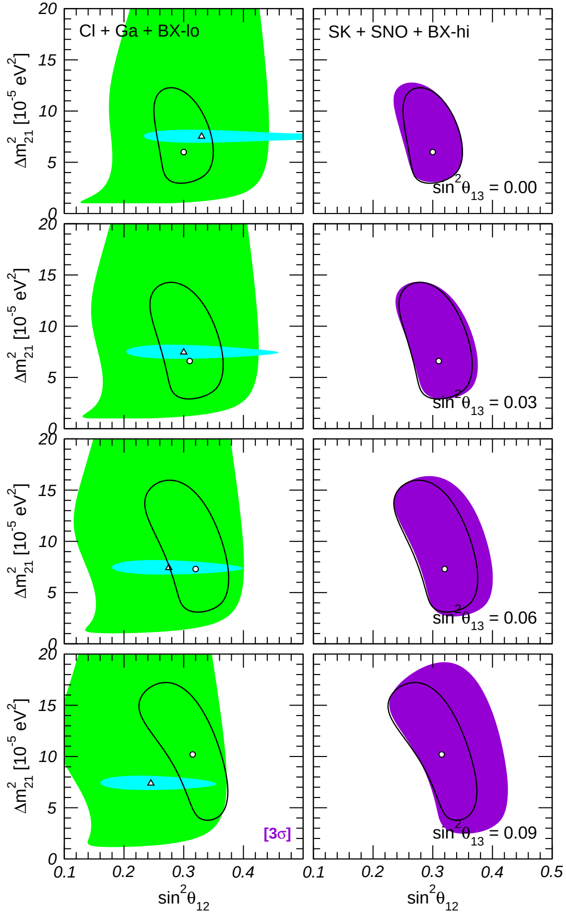


Impact of θ_{13} on solar & KamLAND

- $\nu_\mu \equiv \nu_\tau \Rightarrow$ no sensitivity to θ_{23} and δ_{CP};
- $\Delta m^2_{31} \approx \infty \Rightarrow$ specific Δm^2_{31} value irrelevant;

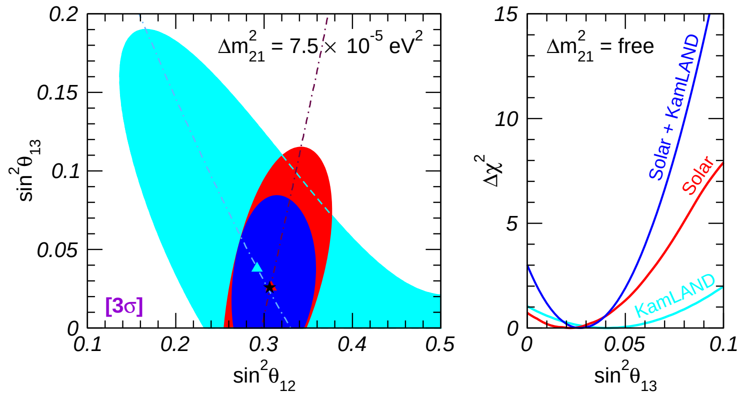
$\Rightarrow$ data only depend on Δm^2_{21}, θ_{12} and θ_{13};

- $P_{ee} \approx \begin{cases} \text{Kam: } \cos^4\theta_{13}\left(1 - \sin^2 2\theta_{12} \sin^2 \frac{\Delta m^2_{21} L}{4E}\right), \\ \text{low-E: } \cos^4\theta_{13}\left(1 - \frac{1}{2}\sin^2 2\theta_{12}\right), \\ \text{high-E: } \cos^4\theta_{13} \sin^2\theta_{12}; \end{cases}$
- as θ_{13} increases, $\cos^4\theta_{13}$ decreases and:
  - KamLAND and low-E data favor **smaller** θ_{12};
  - high-E data favor **larger** θ_{12} and Δm^2_{21};
- synergy between solar and KamLAND data: as θ_{13} increases, Δm^2_{21}: $\begin{cases} \text{increases in solar data;} \\ \text{remains stable in KamLAND;} \end{cases}$
- hence: $\begin{cases} \theta_{13} \textbf{ small} \text{ (but } \neq 0) \Rightarrow \text{better agreement;} \\ \theta_{13} \textbf{ large} \Rightarrow \text{a tension appear.} \end{cases}$



Preference for non-zero θ_{13} from solar + KamLAND data

- For $\theta_{13} = 0$, we have $\sin^2\theta_{12} = \begin{Bmatrix} 0.30 \text{ from Solar data} \\ 0.33 \text{ from KamLAND data} \end{Bmatrix} \Rightarrow$ a tension appear;
- as we have just seen, when θ_{13} increases:
  - solar region slightly moves to larger θ_{12} (high-E data dominate over low-E ones);
  - KamLAND region definitely shifts to smaller θ_{12};
- therefore, a non-zero value of θ_{13} reduces the tension between solar and KamLAND data [1, 2];
- new SNO (I+II+III) analysis favor smaller $\phi_{CC}/\phi_{NC} \Rightarrow$ smaller θ_{12} from solar $\Rightarrow$ tension with KamLAND is increased $\Rightarrow$ larger θ_{13} is preferred.

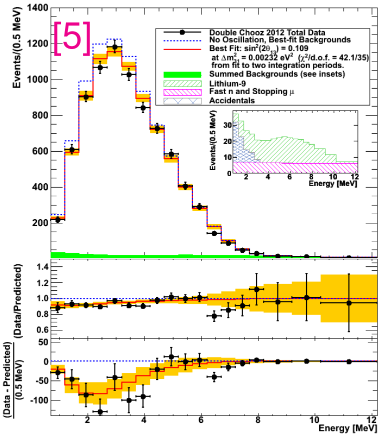


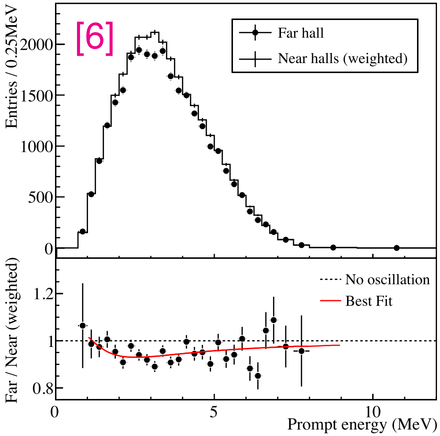
[1] G.L. Fogli *et al.*, Phys. Rev. Lett. **101** (2008) 141801 [arXiv:0806.2649].

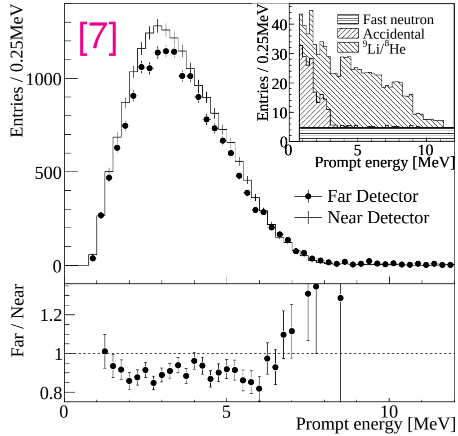
[2] T. Schwetz, M.A. Tortola, J.W.F. Valle, New J. Phys. **10** (2008) 113011 [arXiv:0808.2016].

Reactor sector: the 2012 revolution

- Until summer 2011, only CHOOZ [3] and PALO-VERDE [4] **upper limits** available;
- since then: **positive signal** from DOUBLE-CHOOZ [5], DAYA-BAY [6], RENO [7];
- present status: $\underline{\theta_{13} \neq 0 \ @ \ 9\sigma}$ after inclusion of the data presented at Neutrino 2012.







[3] M. Apollonio *et al.* [CHOOZ], Eur. Phys. J. C **27** (2003) 331 [`hep-ex/0301017`].

[4] F. Boehm *et al.* [PALO-VERDE], Phys. Rev. D **64** (2001) 112001 [`hep-ex/0107009`].

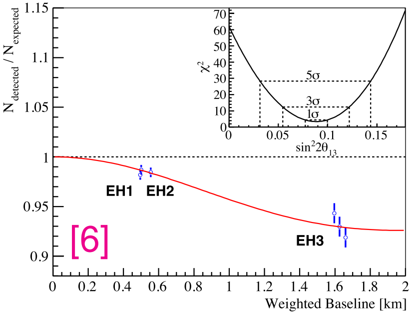
[5] M. Ishitsuka [DOUBLE-CHOOZ], talk presented at Neutrino 2012, 4/06/2012.

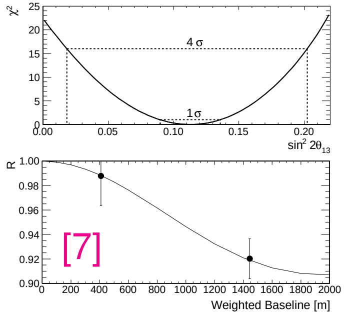
[6] D. Dwyer [DAYA-BAY], talk presented at Neutrino 2012, 4/06/2012.

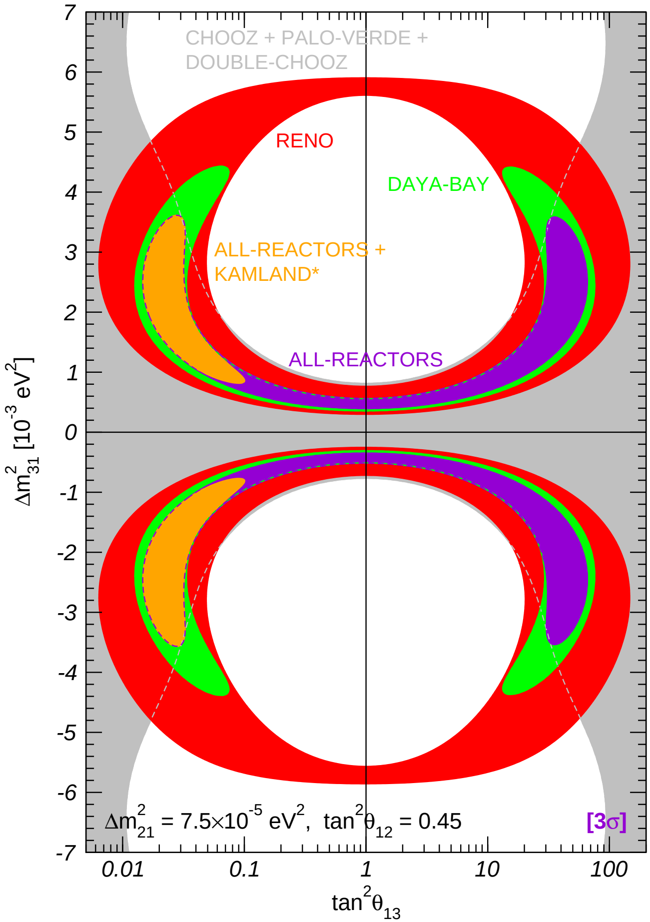
[7] J.K. Ahn *et al.* [RENO], Phys. Rev. Lett. **108** (2012) 191802 [`arXiv:1204.0626`].

Measuring Δm^2_{31} with reactors only

- Sizable deficit at the **far** detector $\Rightarrow$ oscillations $\Rightarrow$ **lower** bound on θ_{13} and Δm^2_{31};
- smaller deficit at the **near** detector $\Rightarrow$ not-too-much oscillations $\Rightarrow$ **upper** bound on Δm^2_{31};
- KamLAND spectrum $\Rightarrow$ **upper** bound on θ_{13}.







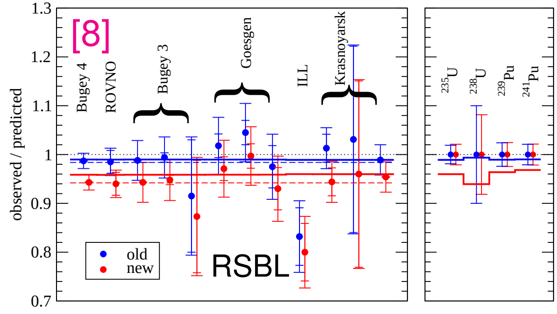
[6] D. Dwyer [DAYA-BAY], talk at Neutrino 2012.

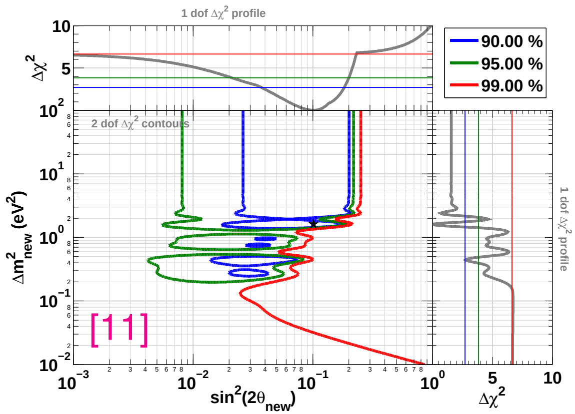
[7] J.K. Ahn *et al.* [RENO], Phys. Rev. Lett. **108** (2012) 191802 [arXiv:1204.0626].

The reactor neutrino anomaly

- In [9, 10] the reactor $\bar{\nu}$ fluxes has been reevaluated;
- the new calculations result in a small increase of the flux by about **3.5%**;
- hence, **all** reactor short-baseline (RSBL) finding no evidence are actually observing a deficit;
- this deficit **could** be interpreted as being due to neutrino oscillations **but** requires $\Delta m^2 \gtrsim 1$ eV^2 $\Rightarrow$ cannot fully accommodate RSBL data within 3ν;
- consistent approach [8]: fit also reactor fluxes (within errors) including **all** reactor data;

$\Rightarrow$ **use of near detector $\Rightarrow$ problem avoided.**

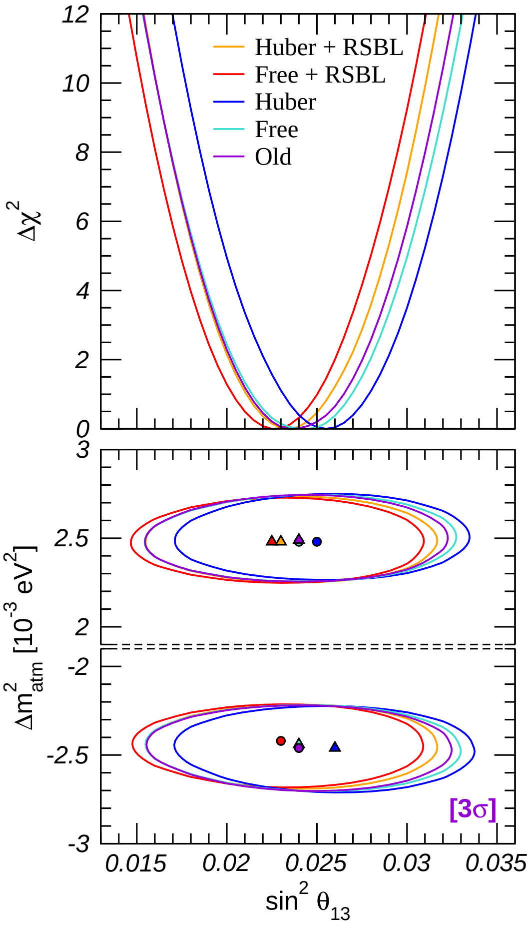




[8] T. Schwetz, M. Tortola, J.W.F. Valle, New J. Phys. **13** (2011) 063004 [arXiv:1103.0734].
[9] T.A. Mueller *et al.*, Phys. Rev. **C83** (2011) 054615 [arXiv:1101.2663].
[10] P. Huber, Phys. Rev. C **84** (2011) 024617 [arXiv:1106.0687].
[11] G. Mention *et al.*, Phys. Rev. **D83** (2011) 073006 [arXiv:1101.2755].

Impact of the reactor neutrino fluxes

- The new fluxes in [9, 10] are **larger** than the old ones, hence they require **larger** suppression to fit data $\Rightarrow$ **larger** θ_{13};
- including RSBL experiments in the fit [8] results in **smaller** fluxes $\Rightarrow$ **smaller** θ_{13};
- once RSBL experiments are included, the specific prior on the reactor fluxes (new or free) has little impact on the results;
- due to their near detector, DAYA-BAY and RENO are almost insensitive to the priors;
- θ_{13} uncertainty from fluxes: $\delta(\sin^2\theta_{13}) = \pm 0.002$.

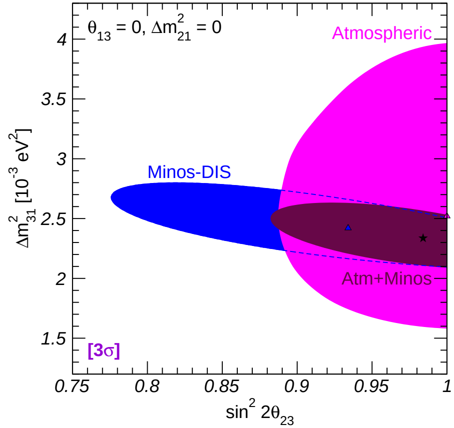


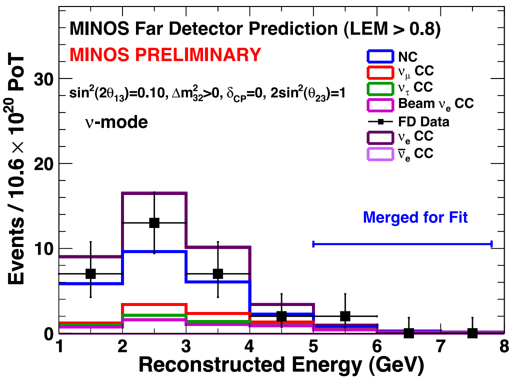
[8] Schwetz *et al.*, NJP **13** (2011) 063004 [arXiv:1103.0734].
[9] Mueller *et al.*, PRC **83** (2011) 054615 [arXiv:1101.2663].
[10] Huber, PRC **84** (2011) 024617 [arXiv:1106.0687].

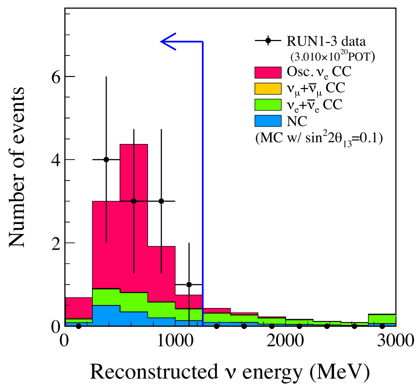
Atmospheric sector: general overview

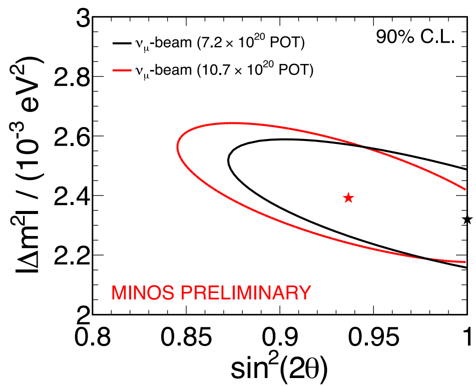
- Δm^2_{31} is now determined by Minos-DIS ($\nu_\mu \to \nu_\mu$) data;
- θ_{23} still dominated by SK atmospheric data;
- θ_{13} & δ_{CP} mostly visible in appearance ($\nu_\mu \to \nu_e$) data; hints of $\theta_{13} \neq 0$ from Minos-APP (2.1σ) and T2K (3.2σ);
- Δm^2_{21} effects visible but only at subleading level;

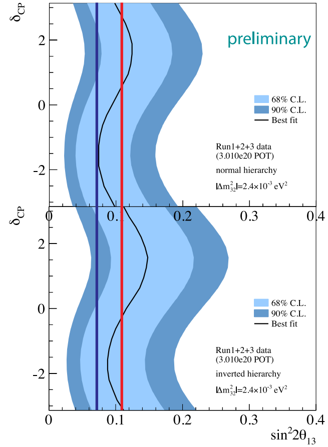
★ **new result**: Minos disappearance data now slightly favor non-maximal θ_{23} mixing.





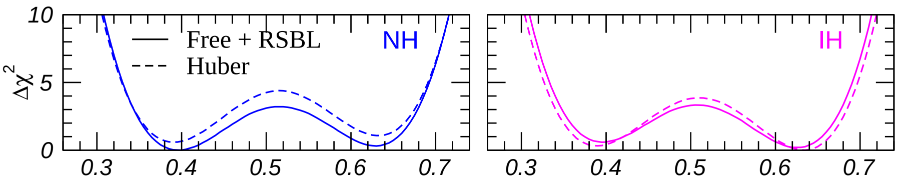


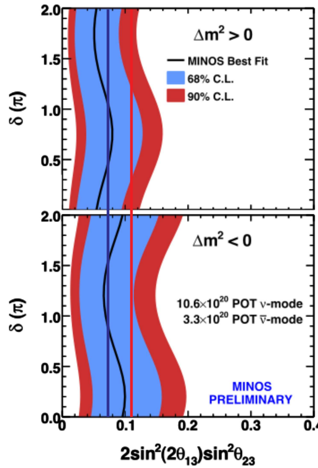




Octant discrimination with REA+LBL data

- In principle, REA + LBL-APP + LBL-DIS can fix the octant [12]:
  - REACTORS: measure $\sin^2(2\theta_{\text{rea}}) \equiv \sin^2(2\theta_{13})$;
  - LBL-DIS: measure $\sin^2(2\theta_{\text{dis}})$, with $\sin^2\theta_{\text{dis}} \equiv \cos^2\theta_{13}\sin^2\theta_{23}$;
  - LBL-APP: measure $\sin^2(2\theta_{\text{app}}) \equiv \sin^2(2\theta_{13})\, 2\sin^2\theta_{23}$ and δ_{CP};
- in practice, putting explicit numbers:
  - from REACTORS: $\sin^2(2\theta_{13}) \simeq 0.09$;
  - from LBL-DIS: $\sin^2(2\theta_{\text{dis}}) \simeq 0.96$ implies $\sin^2\theta_{23} = 0.41$ or 0.61;
  - hence, REA + LBL-DIS imply $\sin^2(2\theta_{\text{app}}) = 0.074$ or 0.110;
- both values of $\sin^2(2\theta_{\text{app}})$ are in similar agreement with LBL-APP;





[12] G.L. Fogli *et al.*, Phys. Rev. D **86** (2012) 013012 [arXiv:1205.5254].
[13] M.C. Gonzalez-Garcia *et al.*, arXiv:1209.3023.

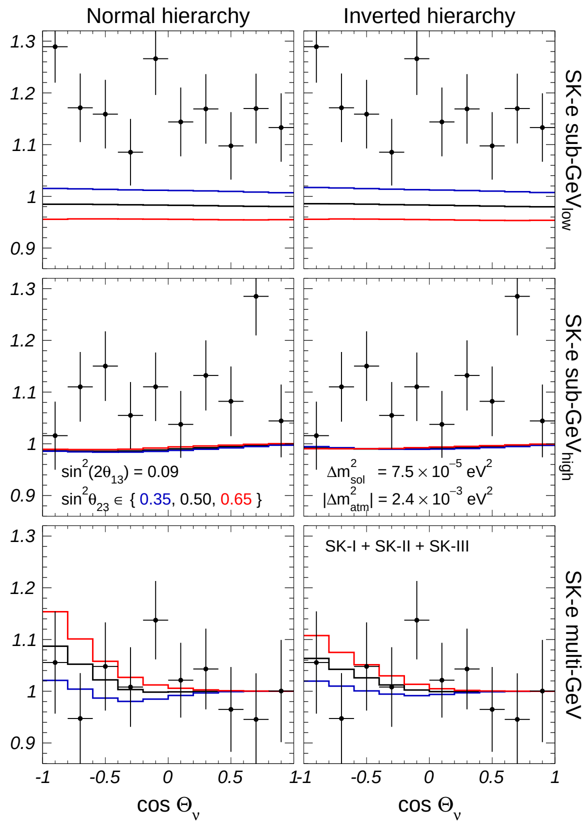
Octant and hierarchy discrimination in atmospheric data

- Excess of e-like events, $\delta_e \equiv N_e/N_e^0 - 1$:

$$\begin{aligned}\delta_e \simeq\ & (\bar r\cos^2\theta_{23} - 1)\, P_{2\nu}(\Delta m^2_{21},\, \theta_{12}) && [\Delta m^2_{21}\ \text{term}]\\ &+ (\bar r\sin^2\theta_{23} - 1)\, P_{2\nu}(\Delta m^2_{31},\, \theta_{13}) && [\theta_{13}\ \text{term}]\\ &- \bar r\sin\theta_{13}\sin 2\theta_{23}\ \mathrm{Re}(A^*_{ee}\, A_{\mu e})\,; && [\delta_{\rm CP}\ \text{term}]\end{aligned}$$

  with $\bar r \equiv \Phi^0_\mu/\Phi^0_e$;

- similar but less pronounced effects also appear in μ-like events (not discussed here);
- resonance in $P_{2\nu}(\Delta m^2_{31},\, \theta_{13}) \Rightarrow$ enhancement of ν ($\bar\nu$) oscillations for normal (inverted) hierarchy $\Rightarrow$ **hierarchy discrimination**;
- δ_e distinguishes between light and dark side $\Rightarrow$ **octant discrimination**;
- **present data**: excess in e-like sub-GeV events $\Rightarrow$ preference for light side.



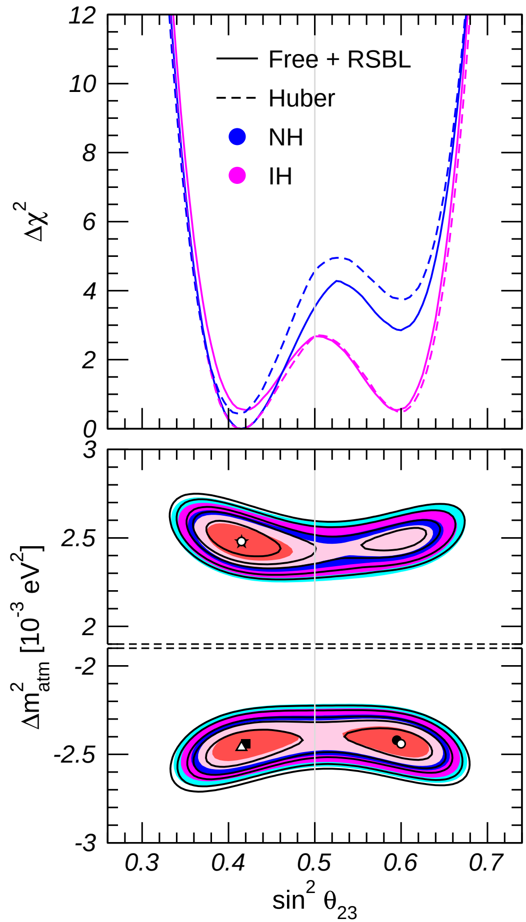
Octant and hierarchy: present status

θ_{23} octant

- Deviation of θ_{23} from maximal mixing **is a physical effect**, which follows from the observation of an excess of events in low-energy e-like data;
- the effect is not statistically significant, but it is well understood and clearly visible;
- unaffected by precise determination of θ_{13};
- found also by other Fogli *et al.* [12], but **not** by SK.

Mass hierarchy

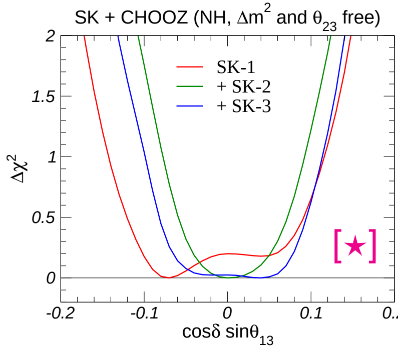
- Matter effects enhanced for larger $\theta_{13} \Rightarrow$ sensitive to rector flux priors;
- small preference for NH or for IH depending on the specific choice of the reactor fluxes.

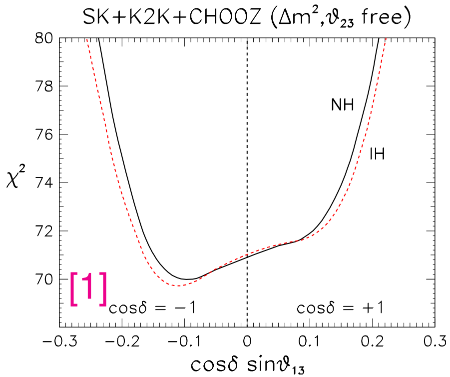


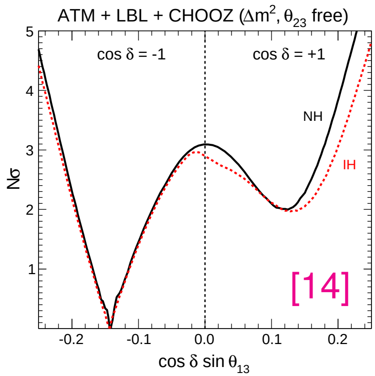
[12] G.L. Fogli *et al.*, PRD **86** (2012) 013012 [arXiv:1205.5254].

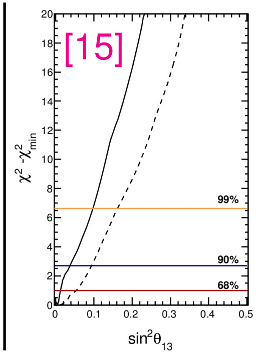
θ_{13} from SK atmospheric data

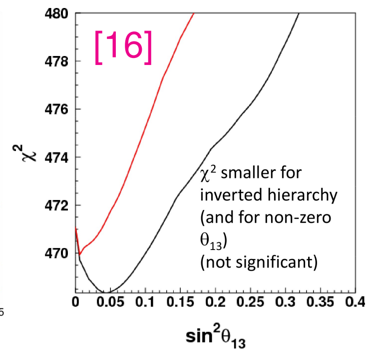
- Hint of non-zero θ_{13} in SK atmospheric data [1, 14];
- no such hint (or very weak one) from our simulation [★];
- ★ details of the simulation very important $\Rightarrow$ SK has final word;
- SK favor $\theta_{13} = 0$ [15] but relevant Δm^2_{21} effects are neglected;
- preliminary full 3ν fit [16] suggests weak deviations (IH only).











[1] G.L. Fogli *et al.*, Phys. Rev. Lett. **101** (2008) 141801 [arXiv:0806.2649].
[14] G.L. Fogli, E. Lisi, A. Marrone, A. Palazzo, A.M. Rotunno, arXiv:1106.6028.
[15] R. Wendell *et al.* [SK], Phys. Rev. **D81** (2010) 092004 [arXiv:1002.3471].
[16] T. Kajita, talk presented at NOW 2010, 7/09/2010.

Neutrino oscillations: where we are

- Global 6-parameter fit (including δ_{CP}):
  - **Solar**: Cl + Ga + SK-I + SNO-full (I+II+III) + BX-low + BX-high;
  - **Atmospheric**: SK-I + SK-II + SK-III + SK-IV;
  - **Reactor**: KamLAND + Chooz + Palo-Verde + Double-Chooz + Daya-Bay + Reno;
  - **Accelerator**: K2K + Minos-DIS + Minos-APP + T2K;
- best-fit point and 1σ (3σ) ranges:

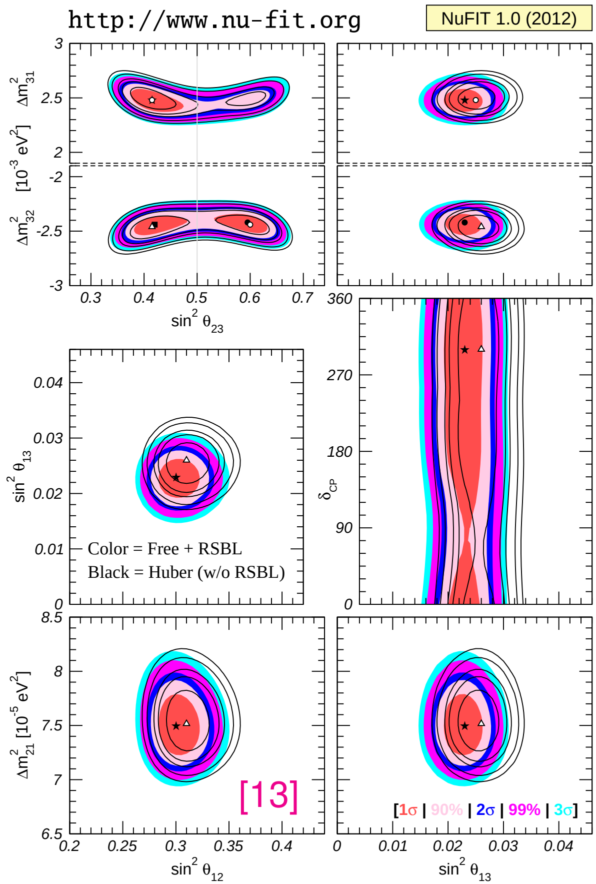
$$\theta_{12} = 33.3 \pm 0.8 \begin{pmatrix} +2.5 \\ -2.2 \end{pmatrix}, \quad \Delta m^2_{21} = 7.50^{+0.20}_{-0.17} \begin{pmatrix} +0.61 \\ -0.48 \end{pmatrix} \times 10^{-5}\ \text{eV}^2,$$

$$\theta_{23} = \begin{cases} 40.0^{+2.1}_{-1.5} \begin{pmatrix} +14.8 \\ -4.2 \end{pmatrix}, \\ 50.4^{+1.2}_{-1.3} \begin{pmatrix} +4.4 \\ -14.6 \end{pmatrix}, \end{cases} \quad \Delta m^2_{31} = \begin{cases} -2.34^{+0.04}_{-0.06} \begin{pmatrix} +0.19 \\ -0.22 \end{pmatrix} \times 10^{-3}\ \text{eV}^2, \\ +2.47^{+0.07}_{-0.07} \begin{pmatrix} +0.22 \\ -0.20 \end{pmatrix} \times 10^{-3}\ \text{eV}^2, \end{cases}$$

$$\theta_{13} = 8.7^{+0.4}_{-0.5} \begin{pmatrix} +1.3 \\ -1.5 \end{pmatrix}, \qquad \delta_{\text{CP}} = 300^{+66}_{-138}\ (\text{any});$$

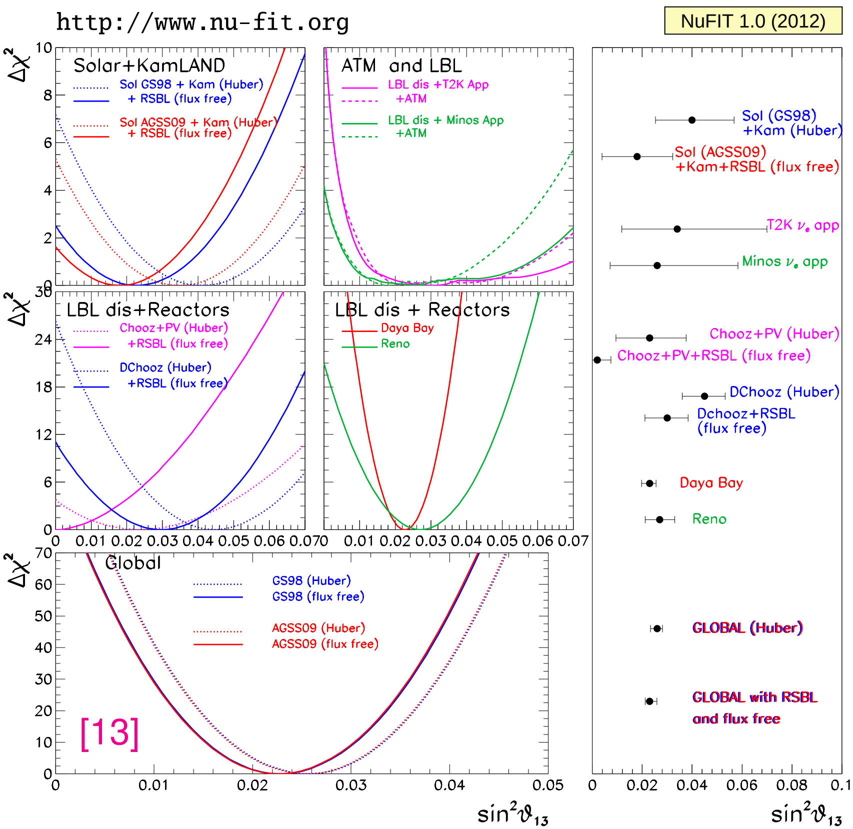
- neutrino mixing matrix:

$$|U|_{3\sigma} = \begin{pmatrix} 0.795 \to 0.846 & 0.513 \to 0.585 & 0.126 \to 0.178 \\ 0.205 \to 0.543 & 0.416 \to 0.730 & 0.579 \to 0.808 \\ 0.215 \to 0.548 & 0.409 \to 0.725 & 0.567 \to 0.800 \end{pmatrix}.$$



[13] M.C. Gonzalez-Garcia, M. Maltoni, J. Salvado, T. Schwetz, arXiv:1209.3023.

- Most of the present data from solar, atmospheric, reactor and accelerator experiments are well explained by the 3ν oscillation hypothesis. **The three-neutrino scenario is robust**;
- the discovery of **large** θ_{13} is a major breakthrough, and marks the beginning of a new phase in neutrino phenomenology.
- the next step involve searching for CP violation, for non-maximal θ_{23} mixing and for the neutrino mass hierarchy. **With present / approved facilities it may not be easy**.



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